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(54) **Enhancement-depletion mode cascode current mirror.**

(57) An improved current source having high output impedance, low saturation voltage, and less sensitivity to process parameters is achieved by having enhancement P-channel transistor devices used as current mirror, while depletion P-channel transistor devices are provided as the cascode devices. A "diode connected" depletion device may be inserted between the enhancement gate and the drain of the current reference transistor to reduce saturation voltage. The "diode connected" depletion device keeps the drains of the enhancement devices at a similar voltage even when the enhancement and depletion device threshold, i.e. V_T, do not track over temperature or process. Thus, the current mirror circuit provides not only higher output impedance, lower saturation voltage, but is also less sensitive to process variation.

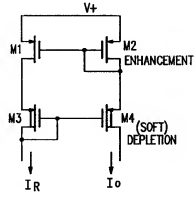

FIG. 11

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Technical Field

This invention relates to current source circuits, particularly to MOS current mirrors.

Background

Current mirrors are well known, and prior art current mirror designs have been implemented both in bipolar and MOS circuit technology. FIG. 1 illustrates an example of a typical prior art P channel MOS current mirror. Ideally, the function of current mirror 10 is to match channel current I_O through transistor M_2, to channel current I_R through transistor M_1, in order that current I_O "mirrors" current I_R. In current mirror 10, diode-connected MOS transistor M_1 is in saturation, since $V_{DS1} \geq V_{GS1}$. With the gate of transistor M_2 connected to the gate of transistor M_1, and the sources of transistors M_1 and M_2 connected, the gate-to-source voltages of transistors M_1 and M_2 are equal ($V_{GS2} = V_{GS1}$). Therefore transistor M_2 also operates in saturation with channel current I_O through transistor M_2 equal to channel current I_R through transistor M_1. This is true for devices operating both above threshold ($V_{GS} \geq V_T$) and in the subthreshold region ($V_{GS} < V_T$). For devices operating above threshold, current I_R through transistor M_1 is expressed as:

$$I_R = \left(\frac{u_{o1}C_{ox1}}{2}\right)\left(\frac{W_1}{L_1}\right)(V_{GS1}-V_{TH1})^2\left(1+\frac{V_{DS}}{V_A}\right) \qquad (1)$$

and current I_O is expressed as

$$I_O = \left(\frac{u_{o2}C_{ox2}}{2}\right)\left(\frac{W_2}{L_2}\right)(V_{GS2}-V_{TH2})^2\left(1+\frac{V_{DS}}{V_A}\right) \qquad (2)$$

where V_A is due to channel modulation (Early Voltage).

Transistors on the same integrated circuit are fabricated simultaneously and thus transistors M_1 and M_2 have essentially identical process parameters V_{TH}, u_O, C_{OX}, etc. Moreover, with $V_{GS2} = V_{GS1}$ due to the circuit connection shown in FIG. 1, the current matching ratio of I_O to I_R may be expressed in simplified terms as

$$\frac{I_O}{I_R} = \frac{W_2/L_2}{W_1/L_1} \qquad (3)$$

where

W_1 = channel width of transistor M_1;
W_2 = channel width of transistor M_2;
L_1 = channel length of transistor M_1; and
L_2 = channel length of transistor M_2.

Thus, the task of selecting a desired I_O/I_R current ratio is simplified to selecting transistor geometry in accordance with Equation (3). Typically, $L_1 = L_2$ in order to avoid matching problems, and thus

$$\frac{I_O}{I_R} = \frac{W_2}{W_1} \qquad (4)$$

However, factors such as channel length modulation;

$$\left(1+\frac{V_{DS}}{V_A}\right), \qquad (5)$$

threshold voltage mismatch between transistors M_1 and M_2, and imperfect matching of transistor geometry also result in deviation from the ideal current ratio I_O/I_R.

The higher the output resistance Ro of a current source, the more perfect it is. Output resistance is proportional to channel length. Ideally $R_O = \infty$, in that the output current will remain constant for varying output voltages. I_O may also fluctuate due to the fact that $V_{DS}(M_1)$ need not necessarily equal $V_{DS}(M_2)$. Thus, the modulation of drain current as the drain voltage varies causes a variation of I_O:

$$\left(1+\frac{V_{DS}}{V_A}\right) I_O = I_O' \qquad (6)$$

FIG. 2 shows a prior art P channel current mirror commonly known as the "Wilson current mirror." Utilizing negative feedback, Wilson current mirror 20 provides an increased output resistance as compared with current mirror 10 of Figure 1. In Figure 2, the sources of transistors M_1 and M_2 are connected together to positive supply voltage V+, and the gates of transistors M_1 and M_2 are connected together. Therefore, the source-gate voltage of transistors M_1 and M_2 are equal. The gate and drain of transistor M_2 are connected together, forcing transistor M_2 into saturation. Transistor M_1 therefore mirrors the current flow through transistor M_2 or, since I_R is made to flow through transistor M_1, current I_O flowing through the channel of transistor M_2 equals I_R. Transistor M_4 isolates the drain of transistor M_2 from the voltage applied to the drain of transistor M_4, thereby preventing any variation in M_4 drain voltage from affecting current I_O. Also, transistor M_4 provides negative feedback to current mirror 20, thereby providing a high output resistance.

FIG. 3 shows a prior art improved Wilson current mirror 30. Current mirror 30 operates similarly to current mirror 20 of Fig. 2, and the addition of transistor M_3 matches V_{DS1} to V_{DS2}. This provides an improvement as compared with the Wilson current mirror of Figure 2 in that the Wilson current mirror 20 allows V_{DS1} to be different than V_{DS2}, providing another source of error.

FIG. 4 shows another well known current mirror commonly known as a cascode current mirror. Cascode current mirror 40 minimizes variations in I_O/I_R due to output resistance R_O. Cascode current mirror 40 is, in effect, a cascade series of 2 current mirrors 10 of Figure 1. In the configuration shown in FIG. 4, assuming all operational parameters of transistors M_1 through M_4 are identical, i.e. the threshold voltages of the devices are identical and $L_1 = L_2$; $L_3 = L_4$; $W_2/W_1 = W_4/W_3$, drain voltage V_{D1} of transistor M_1 equals drain voltage V_{D2} of transistor M_2. If there is a voltage fluctuation increasing the drain voltage of transistor M_4, drain current I_O through transistors M_2 and M_4 remains relatively constant. Current ratio I_O/I_R is thus maintained. Table 1 shows the minimum saturation voltage (V_{satmin}) of each of the current mirrors of Figures 1-4. The current mirror of Figure 1, being the simplest, has the lowest V_{satmin} equal to simply dV_2, where $dV = (V_{GS1} - V_{T1})$, and dV is the overdrive voltage above the threshold voltage V_T. All of the remaining current mirrors of Figures 2-4, being more complex, result in greater V_{satmin}, a distinct disadvantage. However, this is the tradeoff for achieving a high output impedance as provided in the current mirrors of Figures 2-4.

Figures 5-10 depict additional prior art current mirrors which attempt to achieve high output resistances and a relatively low V_{satmin}, although necessarily resulting in a V_{satmin} greater than the V_{satmin} of current mirror 10 of Figure 1. Furthermore, the prior art current mirrors of Figures 5-10 require an additional reference current or are unduly affected by process variations and changes in operating temperature. Therefore, it is desirable to provide a more efficient current source circuit which provides high output impedance, low saturation voltage, and which is unaffected by process variations and changes in temperature.

SUMMARY OF THE INVENTION

An improved current source having high output impedance, low minimum saturation voltage, and less sensitivity to process parameters is achieved by having enhancement mode P channel transistor devices used as current mirror transistors, while a depletion mode P channel transistor is provided as the cascode device. A diode connected depletion transistor may be inserted between the gate and drain of the enhancement mode current reference transistor to provide additional reduction in effective saturation voltage as compared with the use of a diode connected enhancement transistor. The diode connected depletion device keeps the drains of the enhancement devices at a similar voltage even when the enhancement mode and depletion mode device thresholds, i.e. V_T enhancement, does not track V_T depletion over temperature or process. Thus, the current mirror circuit provides not only higher output impedance, lower minimum saturation voltage, but is also less sensitive to process variation.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows an example of a prior art basic current mirror circuit;
FIG. 2 shows an example of a prior art Wilson current mirror circuit in MOS technology;
FIG. 3 shows an example of a prior art improved Wilson current mirror circuit;
FIG. 4 shows an example of a prior art cascode current mirror circuit; FIGS. 5-10 show other prior art current mirrors;
FIGS. 11-13 show various embodiment of an enhancement-depletion mode cascode current mirror constructed in accordance with the principles of this invention;
FIG. 14 shows a graphical comparison of the output current to the output voltage of a current mirror constructed in accordance with the principles of this invention;
FIG. 15 is a schematic diagram of a prior art bipolar voltage reference; and
FIG. 16 is a schematic diagram of one embodiment of a bipolar current mirror constructed in accordance with this invention.

DESCRIPTION OF SPECIFIC EMBODIMENTS

FIG. 11 is a schematic diagram of one embodiment of a current mirror constructed in accordance with the teachings of this invention. Unlike the modified Wilson current mirror described in Figure 3, in accordance with this embodiment of this invention, transistor devices M_3 and M_4 are soft depletion devices, while transistors M_1 and M_2 remain enhancement devices. In this context, a "soft depletion" device is a P channel device having a threshold voltage on the order of 0 volts or a slightly positive threshold voltage, say for example approximately 0.3 volts. Thus, the minimum saturation voltage V_{satmin} for the embodiment of Figure 11 is equal to $V_{satmin} = V_{td} + dV_{dep} + dV_{enh}$. However, with V_{td} equal to 0 or a slightly positive voltage, V_{satmin} is within the range of approximately 2dV, thereby providing a novel current mirror having a high output resistance and a significantly reduced V_{satmin} ascompared with the prior art high output resistance current mirrors. Furthermore, being a relatively straightforward circuit, it is not only compact but is also substantially unaffected by variations in process or changes in operating temperature.

FIG. 12 is a schematic diagram of another embodiment of a current mirror constructed in accordance with the teachings of this invention. Unlike the cascode current mirror described in Figure 4, in accordance with this embodiment of this invention, transistor devices $M_3$and M_4 are soft depletion devices, while transistors M_1 and M_2 remain enhancement devices. The minimum saturation voltage V_{satmin} for the embodiment of Figure 12 is the same as previously described with respect to the embodiment of Figure 11. The embodiment of Figure 12 provides a novel current mirror having a high output resistance and a significantly reduced V_{satmin} as compared with the prior art high output resistance current mirrors, and which is compact and is substantially unaffected by variations in process or changes in operating temperature.

FIG. 13 shows an alternative embodiment of an improved current mirror constructed in accordance with the principles of this invention. Enhancement-depletion mode cascode current mirror 100 utilizes enhancement mode P channel transistors M_1 and M_2 as the "current mirror" transistors, and depletion mode P channel transistors M_3 and M_4 as the "cascode" transistors. With the gate and drain of depletion mode P channel transistor M_3 connected together, transistor M_3 operates as a diode-connected depletion transistor connected between the gate and drain of current reference transistor M_1. $V_T + dV$ of transistor M_3 is close to zero. With diode-connected depletion M_3 transistor and depletion cascode transistor M_4, the drains of transistors M_1 and M_2 are maintained at the same voltage. The mirror of Figure 13 is fully active (i.e. operating as an effective cascode current mirror) down to $dV_4 + dV_2$, and therefore transistors M_4 and M_2

have a very small V_{satmin}. Transistors M_1 and M_2 are maintained in saturation even when the threshold voltage V_{te} of enhancement mode transistors M_2 and M_1 fail to track V_{td} of depletion mode transistors M_6 and M_5 over temperature and process variations. Furthermore, circuit layout is greatly simplified and made more compact by the fact that the gates of transistors M_1 through M_6 are all connected together, as well as minimizing the need to make contacts to source-drain regions.

Moreover, it is envisioned as within the scope of this invention to provide a large channel width to channel length ratio W/L in the fabrication of transistors M_3 and M_4, to further lower the saturation voltage of current mirror 100. It is also envisioned as within the scope of this invention to use enhancement mode N channel transistors as "current mirror" transistors M_1 and M_2, while using depletion mode N channel transistors as "cascode" transistors M_3 and M_4.

FIG. 14 provides a graphical illustration of the high output impedance, achieved by current mirror 100, as compared to the high impedance, higher Vsatmin of a typical prior art current mirror such as current mirror 40 of FIG. 4. By utilizing both enhancement mode and depletion mode devices in current mirror 100, an improved current mirror circuit is provided which results in higher output impedance, lower Vsatmin and less sensitivity to process variation in the fabrication of the circuit devices, while easing layout considerations and achieving highly dense circuit layout.

Figure 16 is a schematic diagram of one embodiment of a current mirror of this invention fabricated utilizing bipolar transistors, which is an improvement over the prior art voltage reference of Fig. 15. Germanium transistors M_3 and M_4 serve the equivalent function of depletion transistors M_3 and M_4 in the MOS embodiment of Figure 14. Similarly, silicon transistors M_1 and M_2 serve the equivalent purpose of enhancement transistors M_1 and M_2 of the MOS embodiment of Figure 13. Thus, the embodiment of Figure 16 provides a bipolar current mirror having the advantages of high output impedance and low V_{satmin}.

Table I characterizes various attributes of the prior art current mirrors of Figures 1-10 and the embodiments of the novel current mirrors of this invention which are depicted in Figures 11-13 and 16.

TABLE I

COMPARISON OF CURRENT MIRRORS-SOURCES

dV = Vgs-Vt, Vte = Vt(enhancement), Vtd = Vt(depletion)

Fig. #	Minimum Saturation Voltage	Output Impedance	Comments-drawbacks good qualities
1	dV	low Z	simple current mirror
2	Vte+2dV	high Z	Wilson mirror, poor matching
3	Vte+2dV	high Z	Modified Wilson mirror, good matching
4	2dV	high Z	Cascode current mirror, large voltage drop on reference side
5,6	2dV	high Z	requires additional bias circuit, current source matches well
7	2dV	high Z	depends on process and temperature
8	2dV	high Z	requires additional bias circuit, current source matches poorly over temperature
11	Vtd+2dV	high Z	Modified Wilson mirror, good matching with depletion-enhancement devices
12	2dV	high Z	Cascode current mirror, with depletion-enhancement devices, low voltage drop on reference side
13	2dV	high Z	process-temperature insensitive (but needs a depletion device)
16	$2dV_{sat}$	high Z (at low temp)	leakage currents a problem, two different technologies

The invention now being fully described, it will be apparent to one of ordinary skill in the art that many changes and modifications can be made thereto without departing from the spirit or scope of the appended claims.

Claims

1. A current mirror circuit comprising:
a first enhancement mode MOS transistor having a source, a gate, and a drain;
a second enhancement mode MOS transistor having a source, a gate, and a drain;
a third depletion mode MOS transistor having a source, a gate, and a drain;
a fourth depletion mode MOS transistor having a source, a gate, and a drain;
wherein the source of the first transistor and the source of the second transistor are coupled to a common voltage source;
the drain of the first transistor is coupled to the source of the third transistor, and the drain of the second transistor is coupled to the source of the fourth transistor;
the gate of the first transistor is coupled to the gate of the second transistor, the gate of the third transistor, and the gate of the fourth transistor; and
wherein the gate of the third transistor is also coupled to the drain of the third transistor to cause the third transistor to operate between the drain of the first transistor and the gate of the first transistor, maintaining the drain of the first transistor and the drain of the second transistor at a similar voltage to generate an output current through the second and the fourth transistor.

2. A current mirror as in claim 1 wherein the first and the second transistors have substantially equal threshold voltages, and the third and the fourth transistors have substantially equal threshold voltages.

3. A current mirror circuit comprising:
a first bipolar transistor having a collector, a base, and a emitter, and having a threshold voltage;
a second bipolar transistor having a collector, a base, and a emitter, and having a threshold voltage;
a third bipolar transistor having a collector, a base, and a emitter, and having a threshold voltage less than said threshold voltage of said first bipolar transistor;
a fourth bipolar transistor having a collector, a base, and a emitter, and having a threshold voltage less than said threshold voltage of said second bipolar transistor;
wherein the emitter of the first transistor and the emitter of the second transistor are coupled to a common ground;
the collector of the first transistor is coupled to the emitter of the third transistor, and the collector of the second transistor is coupled to the emitter of the fourth transistor;
the base of the first transistor is coupled to the base of the second transistor, the base of the third transistor, and the base of the fourth transistor; and
wherein the base of the third transistor is also coupled to the collector of the third transistor to cause the third transistor to operate between the collector of the first transistor and the base of the first transistor, maintaining the collector of the first transistor and the collector of the second transistor at a similar voltage to generate an output current through the second and the fourth transistor.

4. A current mirror of claim 3 wherein the threshold voltages of said first and second bipolar transistors are substantially equal, and the threshold voltages of said third and fourth bipolar transistors are substantially equal.

5. A current mirror circuit comprising:
a first enhancement mode MOS transistor having a source, a gate, and a drain;
a second enhancement mode MOS transistor having a source, a gate, and a drain;
a third depletion mode MOS transistor having a source, a gate, and a drain;
a fourth depletion mode MOS transistor having a source, a gate, and a drain;
wherein the source of the first transistor and the source of the second transistor are coupled to a common voltage source;
the drain of the first transistor is coupled to the source of the third transistor, and the drain of the second transistor is coupled to the source of the fourth transistor;
the gate of the first transistor is coupled to the gate of the second transistor, and the gate of the second transistor is also coupled to the drain of the second transistor to operate between the common voltage source and the gate of the first transistor; and
wherein the gate of the third transistor is coupled to the gate of the fourth transistors, and the gate of the third transistor is also coupled to the drain of the third transistor to cause the third transistor to operate between the drain of the first transistor and the gate of the fourth transistor, maintaining the

drain of the first transistor and the drain of the second transistor at a similar voltage to generate an output current through the second and the fourth transistor.

6. A current mirror as in claim 5 wherein the first and the second transistors have substantially equal threshold voltages, and the third and the fourth transistors have substantially equal threshold voltages.

7. A current mirror circuit comprising:
a first bipolar transistor having a collector, a base, and a emitter, and having a threshold voltage;
a second bipolar transistor having a collector, a base, and a emitter, and having a threshold voltage;
a third bipolar transistor having a collector, a base, and a emitter, and having a threshold voltage less than said threshold voltage of said first bipolar transistor;
a fourth bipolar transistor having a collector, a base, and a emitter, and having a threshold voltage less than said threshold voltage of said second bipolar transistor;
wherein the emitter of the first transistor and the emitter of the second transistor are coupled to a common ground;
the collector of the first transistor is coupled to the emitter of the third transistor, and the collector of the second transistor is coupled to the emitter of the fourth transistor;
the base of the first transistor is coupled to the base of the second transistor, and the base of the second transistor is also coupled to the collector of the second transistor to operate between the common voltage source and the base of the first transistor; and
wherein the base of the third transistor is coupled to the base of the fourth transistor, and the base of the third transistor is also coupled to the collector of the third transistor to cause the third transistor to operate between the collector of the first transistor and the base of the fourth transistor, maintaining the collector of the first transistor and the collector of the second transistor at a similar voltage to generate an output current through the second and the fourth transistor.

8. A current mirror of claim 7 wherein said threshold voltages of the first and the second bipolar transistors are substantially equal, and said threshold voltages of the third and the fourth bipolar transistors are substantially equal.

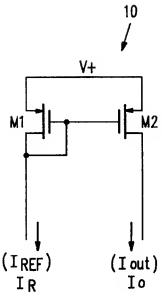
9. A current mirror circuit comprising:
a first enhancement mode MOS transistor having a source, a gate, and a drain;
a second enhancement mode MOS transistor having a source, a gate, and a drain;
a third depletion mode MOS transistor having a source, a gate, and a drain;
a fourth depletion mode MOS transistor having a source, a gate, and a drain;
wherein the source of the first transistor and the source of the second transistor are coupled to a common voltage source;
the drain of the first transistor is coupled to the source of the third transistor, and the drain of the second transistor is coupled to the source of the fourth transistor;
the gate of the first transistor is coupled to the gate of the second transistor, and the gate of the first transistor is also coupled to the drain of the first transistor to operate between the common voltage source and the gate of the second transistor; and
wherein the gate of the third transistor is coupled to the gate of the fourth transistor, and the gate of the third transistor is also coupled to the drain of the third transistor to cause the third transistor to operate between the drain of the first transistor and the gate of the fourth transistor, maintaining the drain of the first transistor and the drain of the second transistor at a similar voltage to generate an output current through the second and the fourth transistor.

10. A current mirror as in claim 9 wherein the first and the second transistors have substantially equal threshold voltages, and the third and the fourth transistors have substantially equal threshold voltages.

11. A current mirror circuit comprising:
a first bipolar transistor having a collector, a base, and a emitter, and having a threshold voltage;
a second bipolar transistor having a collector, a base, and a emitter, and having a threshold voltage;
a third bipolar transistor having a collector, a base, and a emitter, and having a threshold voltage less than said threshold voltage of said first bipolar transistor;
a fourth bipolar transistor having a collector, a base, and a emitter, and having a threshold voltage less than said threshold voltage of said second bipolar transistor;

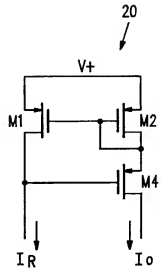
wherein the emitter of the first transistor and the emitter of the second transistor are coupled to a common ground;
the collector of the first transistor is coupled to the emitter of the third transistor, and the collector of the second transistor is coupled to the emitter of the fourth transistor;
the base of the first transistor is coupled to the base of the second transistor, and the base of the first transistor is also coupled to the collector of the first transistor to operate between the common voltage source and the base of the second transistor; and
wherein the base of the third transistor is coupled to the base of the fourth transistor, and the base of the third transistor is also coupled to the collector of the third transistor to cause the third transistor to operate between the collector of the first transistor and the base of the fourth transistor, maintaining the collector of the first transistor and the collector of the second transistor at a similar voltage to generate an output current through the second and the fourth transistor.

12. A current mirror of claim 33 wherein said threshold voltages of the first and the second bipolar transistors are substantially equal, and said threshold voltages of the third and the fourth bipolar transistors are substantially equal.



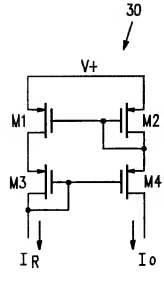
PRIOR ART

FIG. 1



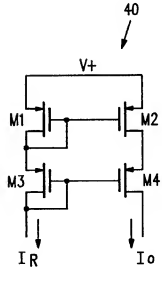
PRIOR ART (WILSON)

FIG. 2



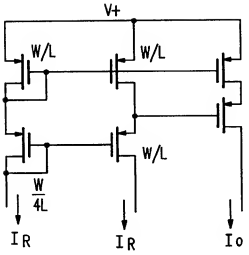
PRIOR ART (MODIFIED WILSON)

FIG. 3



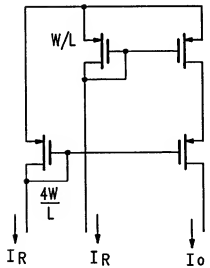
PRIOR ART (CASCADE MIRROR)

FIG. 4



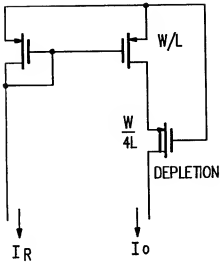
PRIOR ART

FIG. 5



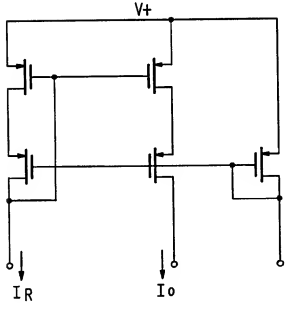
PRIOR ART

FIG. 6



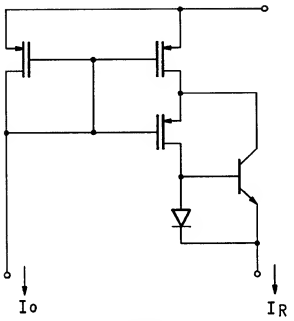
PRIOR ART

FIG. 7



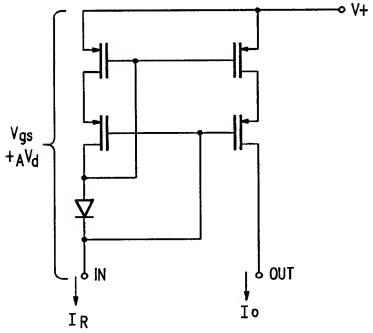
PRIOR ART

FIG. 8



PRIOR ART

FIG. 9



PRIOR ART

FIG. 10

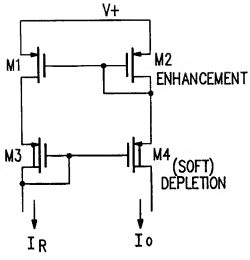


FIG. 11

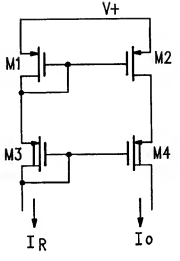


FIG. 12

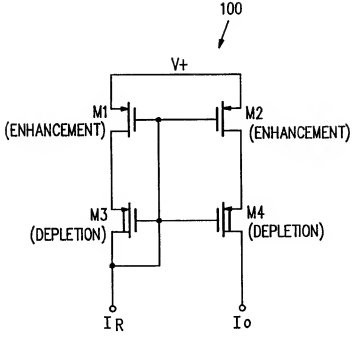


FIG. 13

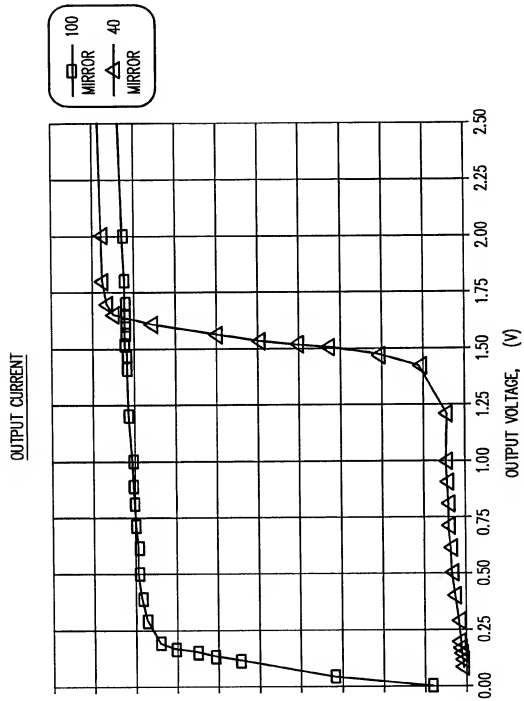
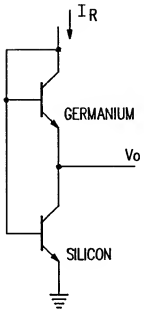

OUTPUT CURRENT
100
MIRROR
40
MIRROR
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
OUTPUT VOLTAGE, (V)

FIG. 14



PRIOR ART

FIG. 15

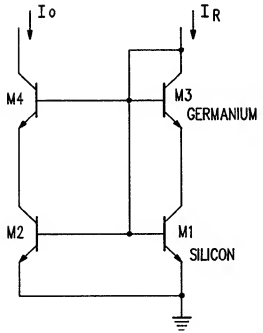


FIG. 16